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A CONNECTION BETWEEN APPARENT VLBA JET SPEEDS AND INITIAL ACTIVE GALACTIC NUCLEUS DETECTIONS MADE BY THE *FERMI GAMMA-RAY OBSERVATORY*

M. L. LISTER[1], D. C. HOMAN[2], M. KADLER[3,4,5,6], K. I. KELLERMANN[7], Y. Y. KOVALEV[8,9], E. ROS[8,10], T. SAVOLAINEN[8], J. A. ZENSUS[8,7]

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ABSTRACT

In its first three months of operations, the *Fermi Gamma-Ray Observatory* has detected approximately one quarter of the radio-flux-limited MOJAVE sample of bright flat-spectrum active galactic nuclei (AGNs) at energies above 100 MeV. We have investigated the apparent parsec-scale jet speeds of 26 MOJAVE AGNs measured by the Very Long Baseline Array (VLBA) that are in the LAT bright AGN sample (LBAS). We find that the γ-ray bright quasars have faster jets on average than the non-LBAS quasars, with a median of 15 c, and values ranging up to 34 c. The LBAS AGNs in which the LAT has detected significant γ-ray flux variability generally have faster jets than the nonvariable ones. These findings are in overall agreement with earlier results based on nonuniform EGRET data which suggested that γ-ray bright AGNs have preferentially higher Doppler boosting factors than other blazar jets. However, the relatively low LAT detection rates for the full MOJAVE sample (24%) and previously known MOJAVE EGRET-detected blazars (43%) imply that Doppler boosting is not the sole factor that determines whether a particular AGN is bright at γ-ray energies. The slower apparent jet speeds of LBAS BL Lac objects and their higher overall LAT detection rate as compared to quasars suggest that the former are being detected by *Fermi* because of their higher intrinsic (unbeamed) γ-ray to radio luminosity ratios.

Subject headings: galaxies: active — galaxies: jets — radio continuum: galaxies — gamma rays: observations — quasars: general — BL Lacertae objects: general

1. INTRODUCTION

The γ-ray emission from highly beamed relativistic jets associated with active galactic nuclei (AGN) most likely originates near the base of the jet where the energetics are strongest (Dermer & Schlickeiser 1994). High-resolution imaging of this region is therefore critical for understanding the mechanism by which high energy radiation is generated. Arguments based on size limits deduced from time variability and the cross section for pair production suggest that the γ-ray emission, like the radio emission, is Doppler boosted (Dermer & Schlickeiser 1994). In fact, the γ-rays may be even more strongly beamed than the radio emission, since the former generally have a steeper spectral index α (where $S_\nu \propto \nu^\alpha$), and the boosting factor is proportional to $\delta^{2-\alpha}$ for continuous jets. Also, Dermer (1995) has shown that if the bulk of the γ-rays are produced by external Compton scattering off photons associated with the accretion disk, then the resulting γ-ray emission will be boosted by an additional factor of $\delta^{1-\alpha}$.

If γ-ray loud AGNs do indeed have systematically high Doppler factors, then we might also expect them to have a distinct apparent speed distribution, since both of these properties depend on the Lorentz factor and viewing angle of the jet. Indeed, Monte Carlo simulations based on a simple linear relationship between radio and γ-ray luminosity (e.g., Lister & Marscher 1999) confirm that in a flux-density-limited radio sample, AGN jets with measurable γ-ray emission above a fixed sensitivity limit should have typically higher speeds than those that are not detected in γ-rays.

Over 65 γ-ray bright radio sources from the EGRET catalogs have been identified with flat spectrum radio-loud AGNs (blazars; Mattox et al. 2001; Sowards-Emmerd et al. 2003, 2004; Casandjian & Grenier 2008). However, the comparison of radio jet structure or kinematics with γ-ray emission has been inconclusive. Kellermann et al. (1998) reported no difference in the morphology of AGN jets with and without observed γ-ray emission. However, using the 2 cm radio data obtained with the NRAO's Very Long Baseline Array (VLBA)[11], Kovalev et al. (2005) found that the radio jets of γ-ray sources appear to have more compact structure than non-γ-ray sources, while Kellermann et al. (2004) used multiepoch 2 cm VLBA data to show that EGRET γ-ray sources have marginally higher jet speeds than non-γ-ray sources. Also, Jorstad et al. (2001) obtained 7 mm and 1.3 cm multiepoch VLBA observations of 33 γ-ray blazars between 1993 and 1997 and reported evidence that AGNs with observed γ-ray emission have somewhat higher appar-

[1] Department of Physics, Purdue University, 525 Northwestern Avenue, West Lafayette, IN 47907, USA;
[2] Department of Physics and Astronomy, Denison University, Granville, OH 43023, USA;
[3] Dr. Remeis-Sternwarte Bamberg, Universität Erlangen-Nürnberg, Sternwartstrasse 7, 96049 Bamberg, Germany
[4] Erlangen Centre for Astroparticle Physics, Erwin-Rommel Str. 1, 91058 Erlangen, Germany
[5] CRESST/NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA
[6] Universities Space Research Association, 10211 Wincopin Circle, Suite 500 Columbia, MD 21044, USA
[7] National Radio Astronomy Observatory, 520 Edgemont Road, Charlottesville, VA 22903-2475, USA;
[8] Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, 53121 Bonn, Germany;
[9] Astro Space Center of Lebedev Physical Institute, Profsoyuznaya 84/32, 117997 Moscow, Russia
[10] Departament d'Astronomia i Astrofísica, Universitat de València, E-46100 Burjassot, Valencia, Spain

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TABLE 1
SAMPLE DESCRIPTIONS

Sample Name (1)	Description (2)	Sources (3)	Reference (4)
LBGS	LAT Bright γ-ray sample	205	Abdo et al. (2009a)
LBAS	LAT Bright AGN List	106	Abdo et al. (2009b)
MOJAVE	MOJAVE radio-selected AGN sample	135	Lister et al. (2009a)
LM	Intersection of LBAS and MOJAVE lists for $\|b\| > 10^{\circ}$	30	This Letter

NOTE. — The LBGS covers the entire sky, with higher limiting flux in the galactic plane and south celestial pole regions. The LBAS excludes the sky region $|b| < 10^{\circ}$, while the MOJAVE survey covers the entire sky north of J2000 declination –20°. There are 106 high-confidence AGN associations in the LBAS, and 11 low-confidence assocations listed in Abdo et al. (2009b) (one of which also has a high-confidence AGN association with the same γ-ray source).

ent speeds. Jorstad et al. (2001) claim an association between the time of γ-ray flares with the ejection of new superluminal components, and that the γ-ray event occurs within the jet features and not at the base of the jet. Lähteenmäki & Valtaoja (2003) found that the γ-ray flaring preferentially takes place during the rising or peak period of the high-frequency radio flares. These EGRET-based results are consistent with models where the γ-ray sources have more highly relativistic jets and are aligned closer to the line of sight.

However, these earlier findings were based on the somewhat limited and inhomogeneous γ-ray data set obtained by the EGRET detector on the *Compton Gamma-Ray Observatory*, with its small number statistics, limited sensitivity, and large position uncertainties, as well as uncertainties introduced by the frequently changing γ-ray catalog lists (Fichtel et al. 1994; Thompson et al. 1995; Hartman et al. 1999; Mattox et al. 2001; Sowards-Emmerd et al. 2003, 2004; Casandjian & Grenier 2008). Thus, it was often ambiguous whether γ-ray emission was detected as a result of a flaring event, or was merely the result of a prescheduled pointed observation, even if the γ-ray and radio sources were clearly associated.

With the beginning of *Fermi* Large Area Telescope (LAT) operations in 2008 August (Atwood et al. 2009), γ-ray observations with greatly improved sensitivity and time sampling are now available for a large sample of AGNs. These data make it possible to recognize and study γ-ray flaring activity with a time resolution of days. At the same time, the continuation and extension of the MOJAVE VLBA program[12] is measuring the velocity and ejection epochs for bright features in over 200 relativistic jets associated with bright radio-loud AGNs (Lister et al. 2009a).

In this Letter, we discuss the parsec-scale jet kinematic properties of AGNs in the radio-flux-limited MOJAVE sample that are associated with bright γ-ray sources detected during the first three months of LAT all-sky survey observations. The latter are $> 10\sigma$ detections from the bright γ-ray source list as reported by Abdo et al. (2009a). The association of these sources with AGNs (the LAT bright AGN sample: LBAS) is discussed by Abdo et al. (2009b). Since the LBAS is not a uniform, flux-limited list of LAT γ-ray detections, the goal of our investigation presented here is mainly to identify general trends in the preliminary γ-ray data. A more detailed and thorough study will be made at the time of the one-year *Fermi* data release, which will contain a uniform all-sky catalog and γ-ray energy spectra of all LAT-detected sources.

Our analysis focuses on the observed MOJAVE jet speeds of the LBAS sources, their redshift, and optical classifications, and how these factors influence their observed γ-ray flux. In an accompanying *Letter* (Kovalev et al. 2009), we report on the correlation of γ-ray flux with quasi-simultaneous parsec-scale radio flux density, radio jet compactness, and overall jet activity level during the three-month initial LAT observation period. A full report on the jet kinematics of all 135 sources in the flux-density-limited complete MOJAVE sample will be presented by Lister et al. (2009b). We use a lambda cold dtark matter (ΛCDM) cosmology with H_0 = 71 km s^{-1} Mpc^{-1}, $\Omega_{\rm m}$ = 0.27, and Ω_Λ = 0.73.

2. COMPARISON OF MOJAVE AND LAT-DETECTED AGN SAMPLES

2.1. *Sample definitions*

The MOJAVE program (Lister et al. 2009a) and its predecessor, the VLBA 2 cm Survey (Kellermann et al. 1998), have been monitoring the parsec-scale jet kinematics of the brightest compact extragalactic radio jets in the northern sky since 1994. The full monitoring sample currently comprises over 200 AGNs, and includes a statistically complete, flux-density-limited subsample of all 135 sources above J2000 declination –20° having VLBA correlated (i.e., compact) flux density above 1.5 Jy (2 Jy for sources south of declination 0°). To account for the variable nature of blazars, the flux density limit applies to a 10-year time period from 1994.0 to 2004.0, i.e., all AGNs that were known to exceed this limit during this time range are included. For the purposes of this discussion, we will hereafter refer to this subsample as the MOJAVE sample. Details of the extensive database search that we conducted to ensure the completeness of the MOJAVE sample are given by Lister & Homan (2005) and Lister et al. (2009a).

The fact that the MOJAVE sample is selected on the basis of relativistically beamed, compact jet emission at centimeter-wavelengths makes it less prone to obscuration effects that can bias other blazar surveys. A detailed study of selection biases by Lister & Marscher (1997) suggests that this type of large, radio-selected sample should contain many of the fastest jets in the parent population, since the latter can have very high Doppler boosting factors (up to $\sim 2\Gamma$, where Γ is the bulk flow Lorentz factor) for favorable viewing angles. This Doppler orientation bias ensures that the MOJAVE sample is composed primarily of jets having high-Γ and low-viewing angles (i.e., flat-spectrum radio quasars and BL Lac objects). Its high blazar fraction and large sky area coverage therefore make it a very useful sample for comparing the radio and γ-ray properties of AGN jets.

Although the MOJAVE sample contains 135 AGNs with declinations above $\delta > -20^{\circ}$, 12 sources lie in the galactic plane region ($|b| < 10^{\circ}$) that is excluded from the LBAS list. For the purposes of our analysis, we will omit these AGNs from the MOJAVE sample. Of the remaining 123 MOJAVE sources, 30 are in the LBAS list (including one low-confidence source listed by Abdo et al. 2009b), which corresponds to an over-

[12] http://www.physics.purdue.edu/MOJAVE

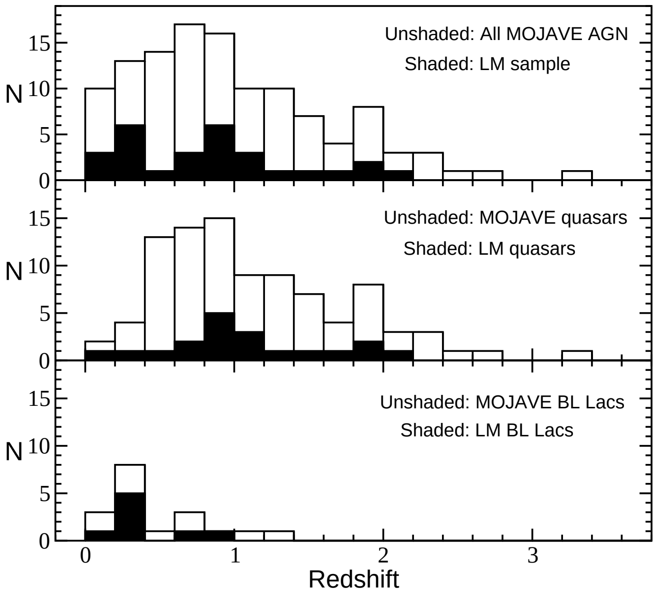

FIG. 1.— Redshift distributions of AGNs in the MOJAVE sample (unshaded). The γ-ray detected (LM) sources in each bin are shaded. The top, middle, and bottom panels show the z-distributions for the full MOJAVE sample, the quasar subsample and the BL Lac subsample, respectively.

all γ-ray detection rate of 24%. Hereafter, we will refer to these LBAS-MOJAVE sources as the LM subset (see Table 1 for a summary of sample descriptions). The LM sources are listed in Table 2, and include 19 out of 94 MOJAVE quasars (20 %), 10 out of 21 BL Lac objects (48 %), and 1 out of six radio galaxies (17 %). Neither of the two optically unidentified MOJAVE sources are in the LBAS list. From a γ-ray sample perspective, 19 out of 41 LBAS quasars (46 %) and 10 out of 31 LBAS BL Lac objects (32 %) north of declination –20° and with $|b| > 10°$ are members of the MOJAVE sample. The only LBAS radio galaxy north of declination –20° is a MOJAVE source (NGC 1275).

For 26 of these 30 bright LM sources, we have measured parsec-scale apparent jet speeds by tracking moving features in VLBA images over periods of several years. In the case of two sources, no redshift information is available; another two were either too compact or show complicated jet kinematics that could not be adequately measured by MOJAVE. We have found that in most jets, the various features typically move with similar but somewhat different speeds (Kellermann et al. 2004). For our analysis, we use the fastest robust speed measured in a given jet, which we consider to be most representative of the speed of the underlying jet flow. The speeds in Table 2 represent the fastest feature in each jet whose motion was determined to be radially outward from the base of the jet and did not show appreciable acceleration. A few isolated jets had no features that met these criteria; in these cases a mean speed from a simple accelerating fit model (Homan et al. 2002) was used. Full details of the speed determinations will be described by Lister et al. (2009b).

2.2. *The Quasar and BL Lac populations*

Compared to the third EGRET catalog (Hartman et al. 1999), the LBAS has a relatively higher ratio of BL Lac objects to quasars. This effect is understood to be the result of a higher detection efficiency of the LAT for sources with harder γ-ray spectra, which is a known characteristic of BL Lac objects (Abdo et al. 2009a). Moreover, the redshift distributions of LBAS quasars and BL Lac objects show two well-separated

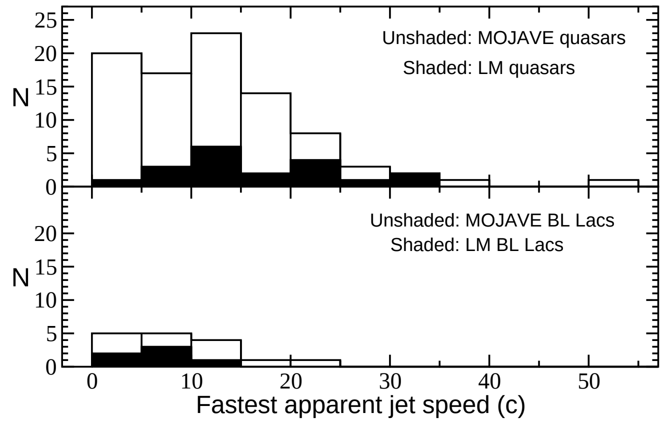

FIG. 2.— Top panel: maximum jet speed distributions for all MOJAVE quasars. The γ-ray detected (LM) quasars in each bin are shaded. Lower panel: same plot for BL Lac objects.

peaks, with the BL Lacs peaking at small redshifts ($z < 0.5$) and the quasars peaking around $z = 1$. The radio-selected MOJAVE sample, on the other hand, is dominated by quasars. In light of possible population differences, we separate the BL Lacs and quasars in our subsequent analysis, noting the better number statistics for the quasars in our sample.

Figure 1 shows the redshift distributions for the MOJAVE sample separated by optical class, with the LM sources shaded. In agreement with the overall LBAS results, the LM BL Lacs tend to dominate the low-redshift part of the distributions, while the distribution of the LM quasars has a maximum close to redshift $z = 1$. A Kolmogorov-Smirnov (K-S) test shows no significant difference between the redshift distributions of the LM and non-LAT-detected MOJAVE AGNs.

2.3. *Apparent parsec-scale jet speeds and γ-ray variability*

In Figure 2 (top panel) we show the distribution of the fastest jet speeds of the 26 LM sources with MOJAVE-measured kinematics. There is a significant difference in the speed distributions of LAT-detected and nondetected MOJAVE quasars. A K-S test gives a probability of only 2.7 % that both distributions are drawn from the same parent distribution. The LM quasars have higher VLBA jet speeds, with a peak in the distribution near $\beta_{\rm app} \sim 10-15c$. Only 5 % of the slowest MOJAVE quasar jets with $\beta_{\rm app} < 5$ are in the LM list. For sources between $\sim 5c$ and $20c$ this rate increases to ~ 20 %, and above $\beta_{\rm app} > 20$ it reaches 50%. Thus, there is a substantially lower LAT detection rate for the MOJAVE quasars with the slowest jet speeds. The statistics for the BL Lac objects are more sparse, and the K-S test indicates no significant difference in the LM and non-LM MOJAVE speeds. However, the speed distributions of the LM BL Lacs and LM quasars are significantly different, (0.3% K-S probability of having the same parent distribution), with medians of $6c$ and $15c$, respectively.

The LBAS list presented by Abdo et al. (2009b) also includes information on which AGNs have displayed significant γ-ray variability ($\delta F/F \gtrsim 0.4$) over the initial three-month LAT observation period. We find that the γ-ray variable LM sources exhibit faster jet speeds (median = $15c$) than the non-variable ones (median = $8c$, see Fig. 3). A K-S test gives a probability of 9.4% that the speed distributions are similar. If only quasars and BL Lacs are considered, this value becomes 5%. The trend is not present in the quasar-only LM sample. All but two of the LM sources with measured VLBA jet

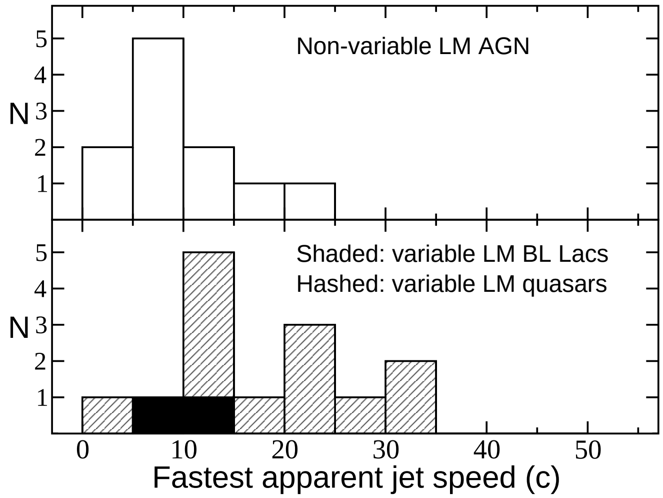

FIG. 3.— Top panel: apparent jet speed distribution for all LM AGNs marked as non-γ-ray variable by (Abdo et al. 2009b). Bottom panel: apparent jet speed distribution for γ-ray variable BL Lacs (shaded) and quasars (hashed).

speeds of $\beta > 15c$ show evidence of γ-ray variability.

3. DISCUSSION

A high apparent speed measurement ($\beta_{\rm app}$, in units of *c*) in an AGN jet implies a minimum Lorentz factor of $\Gamma \simeq \beta_{\rm app}$ and sets an upper limit $\theta < 2$ arctan $\beta_{\rm app}^{-1}$ on the viewing angle. The median LBAS quasar speed of 15*c* thus corresponds to jet viewing angles within 7.6° of the line of sight. Since the observed flaring properties of AGNs are expected to depend strongly on jet speed and viewing angle (Lister 2001), the trend of γ-ray variable LBAS sources having even higher speeds (median = 20*c*, $\theta < 5.7°$) is consistent with earlier EGRET findings (e.g., Kellermann et al. 2004; Kovalev et al. 2005) that these blazars have preferentially higher Doppler boosting factors. While large Doppler boosting factors by themselves may be directly responsible for the observed correlations, there may be an additional dependence of intrinsic γ-ray luminosity on the bulk Lorentz factor of the jet or rest-frame viewing angle, as both of these quantities are also closely tied to the apparent superluminal speed.

The relatively low γ-ray detection rate of the MOJAVE blazar sample in the first three months of LAT operations (24%) would indeed suggest that Doppler boosting is not the sole factor in determining whether a particular AGN is bright at γ-ray energies. For example, only 16 of the 37 MOJAVE AGNs that were high-confidence or probable EGRET associations according to the references cited in Section 1 are in the LBAS list. Since we would not expect the Doppler factors of these jets to change significantly in the intervening time period, this suggests that additional factors are involved.

In an accompanying Letter, (Kovalev et al. 2009) we report that the LM jets tend to be in a relatively active state, as determined by their jet core compactness and radio luminosity levels. Many AGNs also appear to have been detected by the LAT by virtue of their proximity (e.g., the radio galaxy NGC 1275), or their spectral energy distribution (i.e., the BL Lac objects). The slower apparent jet speeds and fainter VLBA radio luminosities of the BL Lac objects suggest that they must have higher intrinsic (unbeamed) γ-ray to radio luminosity ratios than other blazars, in order to account for their higher LAT-detection rate. This can be more fully investigated when the LAT photon energy spectra become available.

4. SUMMARY

We have examined the parsec-scale jet kinematics of a subset of 30 AGNs from the flux-limited MOJAVE VLBA radio sample that were detected during the first three months of *Fermi* LAT observations at energies greater than 100 MeV. Although the LAT three-month bright AGN source list is not a complete flux-limited γ-ray survey, we have identified several trends that merit further investigation with the full one-year *Fermi* data set:

(1) The fraction of MOJAVE AGNs detected by the LAT in its first three months of operations (30 of 123 = 24%) is comparable to the fraction detected by EGRET during its mission lifetime (37 of 123 = 30%). Only 16 of these AGNs were detected by both γ-ray telescopes.

(2) We find no significant difference in the redshift distributions of the LAT-detected MOJAVE (LM) and non-LAT-detected MOJAVE AGNs.

(3) The apparent jet speed distribution of the 19 LM quasars with kinematic information and redshifts is peaked at roughly 10–15*c*, while that of the 70 non-LM quasars peaks below 5*c*.

(4) Of the 26 LM AGNs with kinematic and redshift information, the 15 that are listed as γ-ray variable by Abdo et al. (2009b) have a faster median speed (15*c*) than the non-variable ones (8*c*).

(5) The LM BL Lacs have lower redshifts and a slower median jet speed (6 c) than the LM quasars (15*c*), yet their fractional LAT detection rate is much higher (48% vs. 20%). This is likely because they have higher intrinsic γ-ray to radio luminosity ratios than the MOJAVE quasars.

Although these results are generally consistent with earlier findings based on nonuniform EGRET data that γ-ray blazars tend to have preferentially higher Doppler boosting factors, our results taken together with those of Kovalev et al. (2009) further indicate that the spectral energy shape and current radio jet activity level are also important factors in determining whether a particular AGN is visible at γ-ray energies.

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Facilities: VLBA, Fermi

TABLE 2
LM SAMPLE OF LAT-DETECTED MOJAVE AGNS

Source (1)	LBAS Name (2)	Alias (3)	Class (4)	Var. (5)	z (6)	β_{app} (7)
0048–097	0FGL J0050.5–0928		B	Y	···	···
0109+224	0FGL J0112.1+2247		B	N	0.265	···
0133+476	0FGL J0137.1+4751	DA 55	Q	Y	0.859	13.0 ± 2.5
0215+015	0FGL J0217.8+0146	OD 026	Q	Y	1.715	34.2 ± 2.1
0234+285[a]	0FGL J0238.4+2855	CTD 20	Q	N	1.207	12.27 ± 0.84
0235+164	0FGL J0238.6+1636		B	Y	0.94	···
0316+413	0FGL J0320.0+4131	3C 84	G	Y	0.0176	0.311 ± 0.059
0420–014[a]	0FGL J0423.1–0112		Q	N	0.914	7.35 ± 0.98
0528+134	0FGL J0531.0+1331		Q	Y	2.07	19.20 ± 0.42
0716+714	0FGL J0722.0+7120		B	Y	0.31	10.07 ± 0.35
0735+178	0FGL J0738.2+1738	OI 158	B	N	···	···
0814+425	0FGL J0818.3+4222	OJ 425	B	N	0.245	1.71 ± 0.29
0851+202	0FGL J0855.4+2009	OJ 287	B	N	0.306	5.21 ± 0.40
1055+018	0FGL J1057.8+0138	4C +01.28	Q	N	0.89	8.1 ± 1.4
1127–145	0FGL J1129.8–1443		Q	N	1.184	14.18 ± 0.59
1156+295	0FGL J1159.2+2912	4C +29.45	Q	N	0.729	24.9 ± 1.8
1226+023	0FGL J1229.1+0202	3C 273	Q	Y	0.158	13.44 ± 0.43
1253–055	0FGL J1256.1–0547	3C 279	Q	Y	0.536	20.58 ± 0.79
1308+326	0FGL J1310.6+3220		Q	Y	0.997	20.88 ± 0.68
1502+106	0FGL J1504.4+1030	4C +10.39	Q	Y	1.839	14.8 ± 1.2
1510–089	0FGL J1512.7–0905		Q	Y	0.36	20.2 ± 1.2
1633+382	0FGL J1635.2+3809	4C +38.41	Q	Y	1.814	29.5 ± 1.6
1749+096	0FGL J1751.5+0935	OT 081	B	Y	0.322	6.84 ± 0.78
1803+784	0FGL J1802.2+7827		B	N	0.68	9.0 ± 2.5
1849+670	0FGL J1849.4+6706		Q	Y	0.657	30.6 ± 1.5
2200+420	0FGL J2202.4+4217	BL Lac	B	N	0.0686	4.97 ± 0.30
2201+171	0FGL J2203.2+1731		Q	Y	1.076	1.55 ± 0.33
2227–088	0FGL J2229.8–0829	PHL 5225	Q	N	1.56	8.1 ± 2.1
2230+114	0FGL J2232.4+1141	CTA 102	Q	N	1.037	15.41 ± 0.65
2251+158	0FGL J2254.0+1609	3C 454.3	Q	Y	0.859	14.19 ± 0.79

NOTE. — Columns are as follows: (1) IAU name (B1950.0); (2) LBAS catalog name from Abdo et al. (2009b); (3) alternate name; (4) optical class, where Q = quasar, B = BL Lac, G = radio galaxy; (5) γ-ray variability flag from Abdo et al. (2009b); (6) redshift as tabulated in Lister et al. (2009a); (7) fastest measured radial, non-accelerating jet speed in units of the speed of light.

[a] Low-confidence association in Abdo et al. (2009b).

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